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Eigenvector Analysis of Digital Elevation Models in a GIS: Geomorphometry and Quality Control

Peter L. GUTH

Department of Oceanography, U.S. Naval Academy,
Annapolis, Maryland 21402-5026, U.S.A.
e-mail: pguth@usna.edu

Abstract. Digital elevation models (DEMs) cover a wide range of scales, and allow statisticalanalysis of geomorphometric parameters. At global or continental scale, DEMs covering rectangular quadrangles can be considered random samples. Average quadrangle values can be compared at different DEM scales, and for different physiographic provinces. Three independent variables provide valuable descriptions of terrain: average elevation, average slope, and the degree of terrain organization. DEMs with spacings of 30″ (global coverage), 3″ (continental United States), and 30 m (local United States) provide almost perfect correlations for average quadrangle elevation and slope, although the slope values increase as the DEM spacing decreases. The degree of terrain organization also correlates across DEM scales, but with lower correlation coefficients, especially in areas of lower relief. Terrain variables computed from 10 m and 30 m USGS Level 2 DEMs are essentially identical. Slope algorithms perform differently in different physiographic provinces, and the aspect algorithm performs poorly in low relief areas. Geomorphometric analysis can provide a rapid and effective assessment of DEM quality control, and should be integrated into the DEM production process.

Keywords: Digital-Elevation-Model, Geomorphometry, Slope-Algorithm, Aspect-Algorithm

INTRODUCTION

Digital elevations models (DEMs), rectangular grids of elevation values, provide an unparalleled tool for geomorphometry. DEMs now cover a wide range of scales, from global through continental and regional to local and almost point scales. Analysis can extract a wide variety of parameters relating elevation, slope, aspect and terrain organization. Conversely, geomorphometry provides an ideal tool for assessing the quality of DEMs. Outliers on histograms or bivariate plots of geomorphometric parameters almost always represent flawed DEMs.

At small scales DEM data cover the entire world, but at large scale data availability reflects a bias toward the United States. This bias results from two factors: (1) the United States government has one of the most aggressive programs in the world to produce DEMs, and (2) almost unique in the world, the United States national mapping agencies place no restrictions on their digital data. DEMs with 30 m spacing cover almost all of the United States, and increasing numbers of 10 m DEMs are coming on line. With data spacing ranging

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from almost 10 km to 10 m, available DEMs span 4 orders of magnitude. Experimental 1 m resolution LIDAR (Light Detection and Ranging) DEMs cover areas almost point-like with vast quantities of data (NOAA Coastal Services Data Center, 2001), and will add another order of magnitude to range of scales when they become widely available.

DATA

This study used DEMs from continental scale (30″ spacing, about 1 km), regional scale (3″ spacing, 60–90 m), and local scale (10–30 m spacing). Table 1 summarizes the free data obtained from the www. These data sets will now fit comfortably on hard disks of mainstream personal computers. All of these data sets use binary 2 byte elevations. The continental data sets are stored uncompressed, whereas the other data sets are stored with the same standard UNIX compressed file structure obtained from the USGS web site. Because compression varies with the type of terrain and the amount of smoothing from the DEM creation process, the estimates below should be viewed only as rough estimates for the order of magnitude of the DEM sizes. Further, if future large scale DEMs use 4 byte values for elevation as the USGS is starting to implement, file sizes might double.

Three different United States government mapping agencies have created quasi-independent continental 30″ DEMs: DTED Level 0 (NIMA, 2000), GLOBE (NOAA National Geophysical Data Center, 2001), and GTOPO30 (USGS EROS Data Center, 2001). After downloading, the GLOBE and GTOPO30 datasets were converted to 1° tiles to match the DTED, and provide a good statistical sampling unit for comparisons. With 1° elevation tiles each data set will fit on a single CD-ROM, if some of the interior cells in Antarctica are removed. The flatness of the ice sheet and the convergence of the meridians make the 30″ DEM a poor choice for the polar regions.

The 250K DEM (USGS, 2001) was originally created by a precursor of NIMA and contains many processing anomalies but remains a valuable regional data resource because of its availability. The current NIMA product, DTED Level 1, provides a much better demonstration of what this data resolution can achieve but is unfortunately not publicly available. The DEMs used in this study cover all of the United States and Puerto Rico except for Alaska. The SRTM mission

Table 1. DEMs available for comparison.

Name	DEMs in Sample	Tile	Spacing	Sample Storage	Full US	Full World
ETOPO5 TerrainBase	1		5’	20 MB		20 MB
DTED0 GLOBE, GTOPO30	17,680 21,803 20,151	1°	30”	650 MB		650 MB
USGS 250K	940	1°	3”	1 GB	1 GB	20 GB
USGS 24K	50,279 (42,921 unique)	7½’	30 m	6.2 GB	6.2 GB	150 GB
USGS 24K	1066	7½’	10 m	1 GB	50 GB	1 TB

should produce this world-wide data set for public use (Jet Propulsion Laboratory, 2001), and the first samples covering some of the United States appeared in early 2002 and South America in the summer of 2003. The SRTM data appeared too late to include in this analysis, and will require careful consideration on how to handle the data voids when conducting statistical analyses.

Over 51,000 24K DEMs were downloaded from the same USGS site along with the 250K DEM (USGS, 2001) in the summer of 2000, before the 24K DEMs were removed. USGS allowed an automated download process, the only practical way to obtain such a large sample. This data, and an increasing number of 10 m DEMs, must now be downloaded free from two commercial sites that restrict the speed or number of DEMs that can be, and which forbid the use of automated ftp, or in a reprojected format from the National Elevation Dataset (NED, Gesch and others, 2002). While the data considered here have elevations stored as 2 byte integers with foot or meter resolution, some newer DEMs now use 2 byte integer decimeters and others use 4 byte floating point values.

The 24K DEMs have two characteristics relevant to a discussion of geomorphometry. The "Level" of the DEM assesses its quality: Level 1, no longer being produced, used profiling or similar photogrammetric methods to produce lower quality DEMs, whereas the newer Level 2 DEMs used interpolation from scanned contour lines (USGS National Mapping Division, 1997/1998). Except for contour line "ghosts" where elevations corresponding to the source map contour lines are overrepresented in the DEM (Guth, 1999c), the Level 2 DEMs provide a much better representation of the terrain. In addition, some DEMs have both 10 m and 30 m resolution. Ten meter resolution provides much greater visual detail in representations of the terrain.

At 30 m spacing the data set includes 42,921 (80%) of the 53,873 24K quadrangles in the continental United States, plus 81 DEMs in Puerto Rico and the Virgin Islands, and provides an excellent sample for this scale data at continental resolution. Hawaiian data were not available on the USGS web site, and Alaska was not mapped at this scale. The SRTM mission (Jet Propulsion Laboratory, 2001) should produce this world-wide data set for US military use, although the radar's smoothing might make the effective resolution lower than the nominal resolution. The data set includes about 1000 10 m level 2 DEMs, or about 2% of the total area of the continental United States.

The following tests on the differences in calculated statistical parameters will be conducted using these DEMs for geomorphometry:

1. How do the different 30″ continental DEMs differ?
2. How do the 30″ continental and 3″ regional DEMs differ?
3. How do the 3″ regional and 30 m local DEMs differ?
4. How do the Level 1 and Level 2 local DEMs differ?
5. How do the 10 m and 30 m Level 2 local DEMs differ?

GEOMORPHOMETRIC PARAMETERS

Pike (1988) introduced the concept of a geometric signature, a multi-variate description of topography using a suite of measures, and later expanded the

concept with a listing of 49 variables that could be grouped into 22 attributes (Pike, 2001). He considered roughness and height the two most important attributes, with two measures of texture in seventh and eleventh position. Fifteen different variables contribute to roughness.

This analysis will focus on three geomorphic parameters: average elevation, average slope, and organization strength. These parameters reflect the interaction of climate, lithology, and topography. Average elevation, combined with latitude, represents a primary control on climate for both precipitation and temperature. Slope depicts the ruggedness and dissection of the landscape. Organization values measure the processes responsible for terrain formation; the most highly organized regions are in folded mountain belts or glacial drumlin fields. Average elevation and average slope coincide with Pike's (2001) most important attributes, but none of his experimental measures fully capture this organization parameter.

Computation of average slope requires selection of a slope algorithm; a number have been proposed, and about a half dozen widely used (recent summaries in Skidinore, 1989; Guth, 1995; Hodgson, 1998; Jones, 1998). Results for average regional slope correlate very strongly among the various methods, although the absolute values vary. This analysis uses the steepest adjacent neighbor algorithm, but comparisons between the steepest adjacent neighbor and four nearest neighbor methods show how the choice of slope method affects geomorphic results.

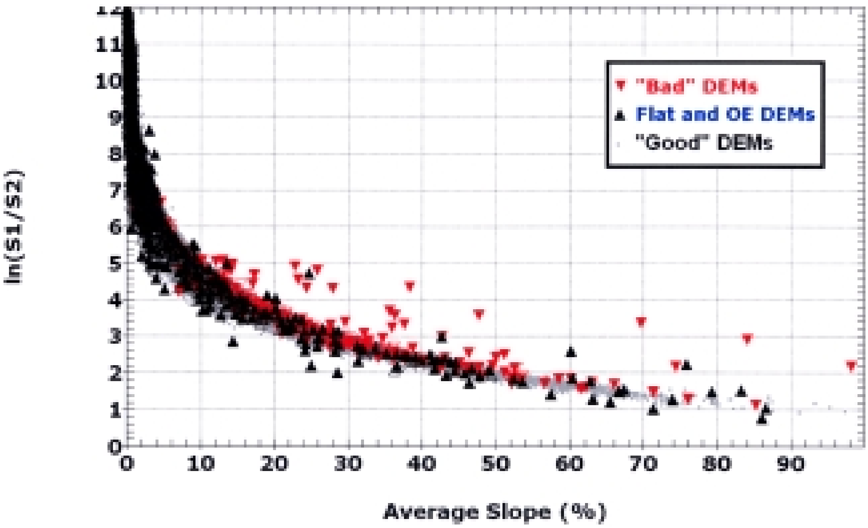

Fig. 1. Average slope versus flatness parameter ln(S1/S2) for the 51,000 24K USGS DEMs. The "good" DEMs show the high correlation. Outliers consist of "bad" DEMs (visually examined to verify processing anomalies) and flat and overedge DEMs (identified by small compressed file sizes).

Eigenvector methods can retrieve a flatness parameter and organization parameter. Chapman (1952) proposed a graphical method using a stereo net to characterize terrain orientations. Woodcock (1977) described an eigenvalue method for fabric shapes in structural geology. The two methods can be combined for automatic characterization of terrain organization (Guth, 1999a, 1999b, 2001). Direction consines of the landscape surface were computed from the slope and aspect at each point, and then eigenvectors were obtained. The eigenvalue method extracts two independent parameters from the distribution of normals to the earth's surface calculated from the DEM, both logs of the ratios of eigenvalues. The ratio ln(S1/S2) reflects a flatness parameter, and it correlates almost perfectly with the average slope (Fig. 1). The correlation is negative because the log ratio is flatness and not steepness, and is not linear because of the log ratio. This correlation should not be surprising, since the eigenvalue method starts with the slope and aspect at each point and the orientation of the first eigenvector is the average normal to the earth's surface.

The ratio ln(S2/S3) reflects the strength of the preferred orientation shown by Fig. 2. No previously defined geomorphic parameters replicate its power in quantifying the degree of organization of the terrain. Other parameters attempt to measure the spatial dimensions of periodic landforms, with "grain" representing the distance between repeating landforms. Based on analysis of over 50,000 30 m DEMs, Fig. 2 shows the three most highly organized quadrangles in the United States. The figure shows the dominant direction of the fabric, defined by the orientation of one eigenvector, and shows how it swings around as the folded ridges change orientation along strike.

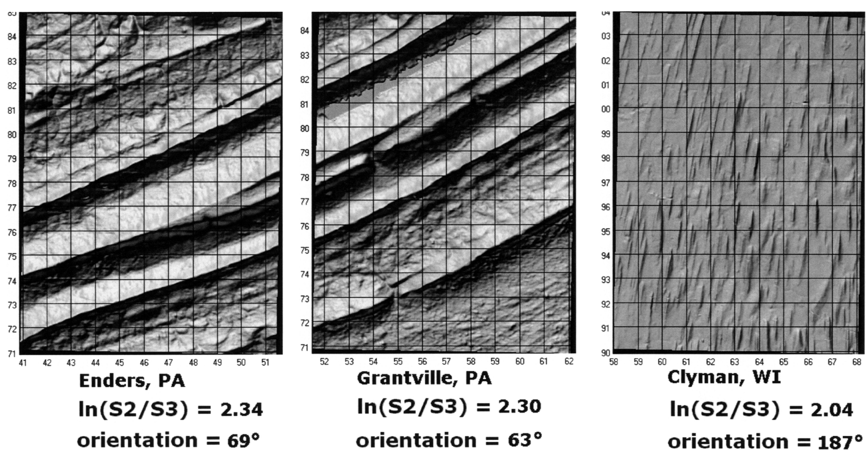

Fig. 2. The three most highly organized quadrangles in the United States. The two on the left are adjacent Level 1 DEMs in the folded Appalachians, and the level 2 DEM on the right contains a drumlin field in Wisconsin. One km UTM grid provides scale.

Elevation is a true point parameter, defined at every grid location in the DEM. While slope is also a point parameter, it requires consideration of the neighboring elevations and various algorithms use from 2 to 8 adjacent neighbors. The most commonly used algorithm uses four neighbors and actually ignores the elevation of the central point to which the slope is assigned. The eigenvector method uses a region and probably requires at least 100 points for reasonable statistical accuracy. While organization can be calculated as a point parameter for a particular region size about a point with a sliding window over the DEM (Guth, 1999b, 2001), this study will concentrate of calculations with a 1° region size for global scale or 7 1/2′ region for continental scale. This quadrangle geomorphometry introduces arbitrary aspects to the study, but sample sizes are large enough that quadrangles represent reasonable sampling areas.

METHODS

All analyses used the MICRODEM program (Guth and others, 1987; Guth, 1995). This program predates commercial GIS programs for personal computers, and while MICRODEM has now become a full-feature GIS program it retains a greater emphasis on DEMs and geomorphometry than any commercial program. While scripting within a GIS might duplicate the operations described here (e.g. contour line ghosts or terrain organization), I prefer embedding the capabilities within MICRODEM where I have complete control of the operations and displays. With object-oriented programming, the DEM object contains methods to calculate geomorphic parameters of the terrain.

MICRODEM indexes the DEMs, and sequentially processes them to calculate geomorphic parameters. For the 30″ global DEMs the program used 1° tiles. For the 3″ 250K DEM, the comparison used 1° tiles to compare with the 30″ data, and 7 1/2′ tiles to compare with the 24K DEM. The program computed five variables for each tile: average slope, average elevation, the eigenvalue flatness and organization parameters, and the direction of terrain organization. The database contains five additional fields for the DEM name and its bounding geographic rectangle. The program computed 28 additional parameters for the 24K DEM: duplicate variables to compare slope algorithms, DEM quality measures like the ghost ratio (Guth, 1999c), and additional geomorphometric parameters which will not be discussed here but which could be used for a geometric signature (Pike, 2001).

The GIS database files for the geomorphic parameters allows summary statistics, bivariate scatter plots, and map displays, with options to filter the display—for example, to only show terrain organization for regions with greater than a specified average slope. The interactive nature of the GIS allows clicking on a point on the graph to show tabular data for that point and its location on the map. For the large data sets considered in this effort, the power of the GIS represents the most effective way to explore the data.

Drawing on earlier work of Fenneman dating to 1917, the Fenneman and Howard (1946) map of the United States has 8 major divisions, 25 provinces, and 86 sections representing distinctive areas having common topography, rock types

and structure, and geologic and geomorphic history. A digital version of the map (Hitt, 2002) was converted to geographic coordinates, and then each quadrangle in the United States was assigned to the corresponding section. This allows the GIS to compute statistics based on the Fenneman physiographic regions.

Many of these analyses omit 24K DEMs identified as containing “bad” data, and those with a compressed file length less than 50 kb. Small file sizes occur in two cases: coastal “overedge” DEMs where standard quadrangles leave a small bit of land in what would be the next quadrangle, and extremely flat quadrangles in regions like the coastal plains. These DEMs account for a disproportionate number of the outliers on statistical plots. Overedge DEMs have an insufficient number of points for reliable statistics, and the DEMs do not have adequate vertical resolution for good statistics in very flat regions. The GIS also contains a percent ocean field for the global data sets; often the coastal DEMs should be ignored for the eigenvector analysis. The 30″ 1° tiles contain only about 1400 elevations, and when a significant proportion are missing the resulting statistics represent outliers compared to full data sets.

SLOPE ALGORITHMS

While different slope algorithms correlate highly, they produce different results. Guth (1995) suggested using a steepest adjacent neighbor algorithm, while the most popular algorithm appears to be the four nearest neighbors (e.g. Hodgson, 1998; Jones, 1998), although Evans (1998) makes a convincing case for the superiority of an eight neighbors algorithm. Because the steepest adjacent neighbor and four nearest neighbors have the greatest differences among the common methods, a detailed analysis of their differences highlights the effect of slope algorithm on geomorphic parameters. Because slope and aspect provide the raw input to the eigenvector algorithm, the slope algorithm might affect the organization calculations.

With an eight point neighborhood about the central point, eight partial slopes can be calculated in each of the eight principal cardinal directions. If the point elevations are considered accurate, these represent the only unambiguous slopes that can be determined. The challenge for the slope algorithm is to use these values to estimate a single slope at the central point. The steepest adjacent neighbor algorithm uses the steepest of the eight slopes: this slope exists, it is measured over the DEM spacing (or the diagonal), and in many applications the steepest slope is most important. The four nearest neighbors algorithm uses just four neighbors: it is measured over twice the DEM spacing, and it smooths the results by using twice the slope distance and not using the diagonal neighbors.

Figure 3 shows a comparison of the average quadrangle slope computed from these two algorithms for 30 m DEMs (28,479 level 2 and 18,689 level 1). This analysis omits DEMs identified as containing bad data, and those with a compressed file length less than 50 kb.

Several observations are clear from the two graphs: (1) the two slope algorithms are highly correlated; (2) the steepest adjacent neighbor algorithm produces consistently larger average slopes; (3) the level 2 DEMs appear to be

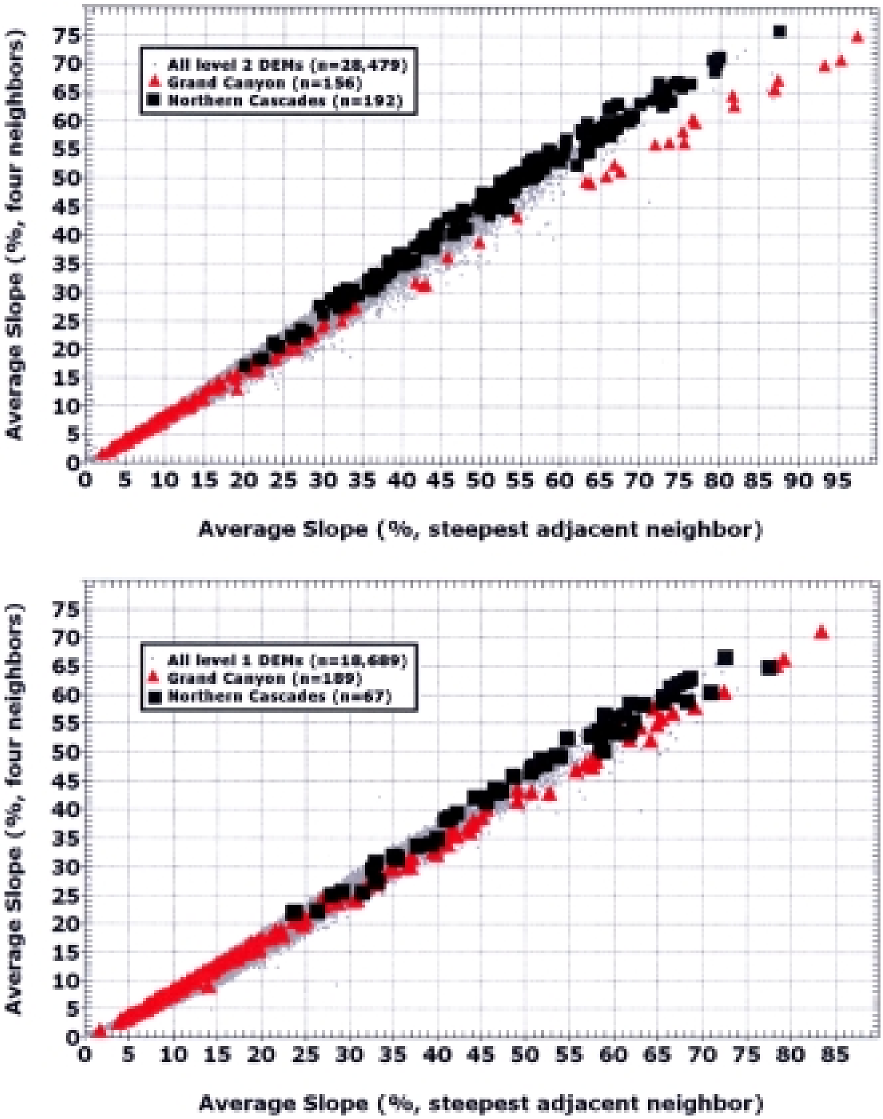

Fig. 3. Average slope computed by two different algorithms, for both Level 1 and Level 2 USGS 24K DEMs. DEMs from two Fenneman physiographic provinces indicated.

steeper than the level 1 DEMs, with both algorithms (this is not proven by these graphs because the DEMs in the two samples are not the same, but it will be proven later); (4) the wide scatter about the trend lines suggests that additional factors affect the slopes.

Table 2. Comparison of slope algorithms for two mountainous quadrangles.

	Temple of Sinawava, Utah		Cascade Pass, WA	
	Steepest Neighbor	Four Neighbors	Steepest Neighbor	Four Neighbors
Entire DEM	86.7%	63.8%	87.5%	75.7%
Peaks	101.2	33.4	130.7	35.8
Other	86.0	64.6	87.6	75.7

Table 3. Comparison of correlation coefficient *r* for geomorphometric parameters.

DEM scales compared	Average Elevation	Average Slope	Organization ln(S2/S3)
DTED0 vs GLOBE, n=17,559	r=0.992	r=0.975	r=0.598
DTED0 vs GTOPO30, n=17,547	r=0.992	r=0.950	r=0.516
GLOBE vs GTOPO30, n=20,114	r=0.999	r=0.979	r=0.906
DTED0 vs USGS 250K, n=946	r=1.000	r=0.983	r=0.680
GTOPO30 vs USGS 250K, n=938	r=0.999	r=0.987	r=0.701
GLOBE vs USGS 250K, n=941	r=0.999	r=0.987	r=0.670
USGS 250K vs 24K, n=51,345	r=0.997	r=0.951	r=0.496
USGS 24K, Level 2, 10 vs 30 m, n=472	r=1.000	r=0.998	r= 0.960
USGS 24K, Level 1 vs 2, 30 m, n=6476	r=1.000	r=0.968	r=0.545

To investigate the effect of additional factors on the computed average slopes, two level 2 DEMs were selected from the steeper side of the graph. Both had similar average slopes using the steepest adjacent neighbor method, but greatly different slopes for the four adjacent neighbors method (Table 2).

As noted by Guth (1995), these two algorithms will differ most for peaks, pits, ridges and valleys. Pits are extremely rare, both in nature and the DEMs, but the other terrain types occur about in 5–6% of the points in these DEMs. While the differences in these points can be huge (see the results for peaks in Table 2), it is the other points that make the difference—the 95–96% of the points classified as “other” have average slopes almost identical to the averages for the entire DEM (Table 3). On this measure these two DEMs differ significantly.

Analysis of the graphs in Fig. 3 revealed that the high slope DEMs occurred primarily in two geomorphic provinces, the Grand Canyon and the Northern Cascades. A few equally steep DEMs occur in other provinces, including the Temple of Sinawava DEM in the High Plateaus of Utah Section adjacent to the Grand Canyon. Highlighting those provinces on the graph showed two very distinct trends: the four adjacent neighbors method produces gentler slopes in the Grand Canyon than in the Northern Cascades, for DEMs that the steepest adjacent neighbor method considered equally steep. Figure 4 shows shaded relief depictions of these two DEMs. The Temple of Sinawava quadrangle has more youthful dissection. More points have extreme slopes along one of the diagonals, and these influence the average slope of the quadrangle only with the steepest adjacent neighbor. The commonly used four neighbors slope algorithm behaves differently

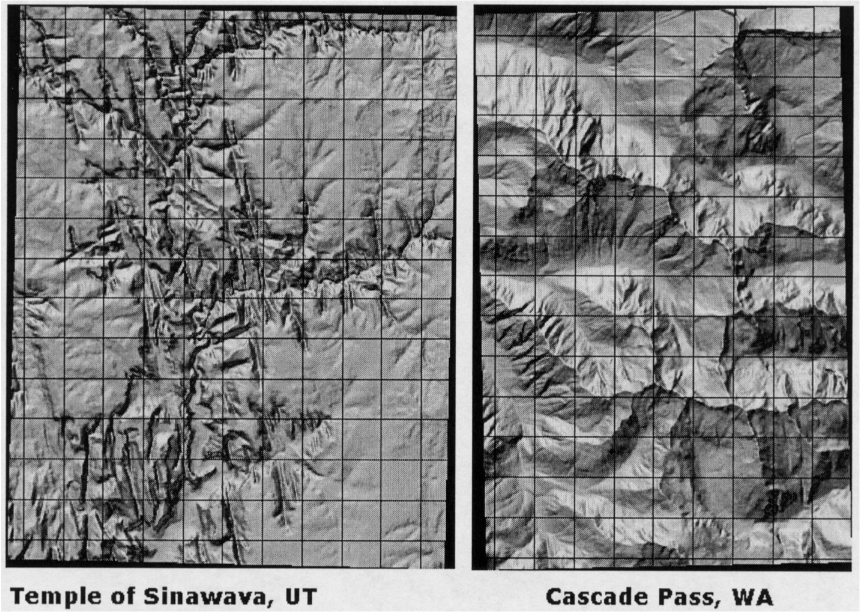

Fig. 4. Shaded relief views to Level 2, 30 m USGS DEMs of Temple of Sinawava and Cascade Pass.

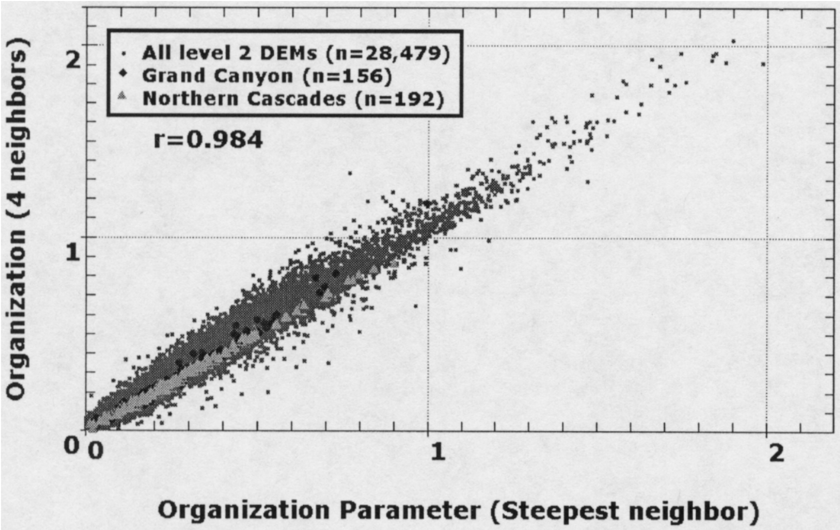

Fig. 5. Organization parameter for 30 m Level 2 USGS DEM calculated with two different slope methods.

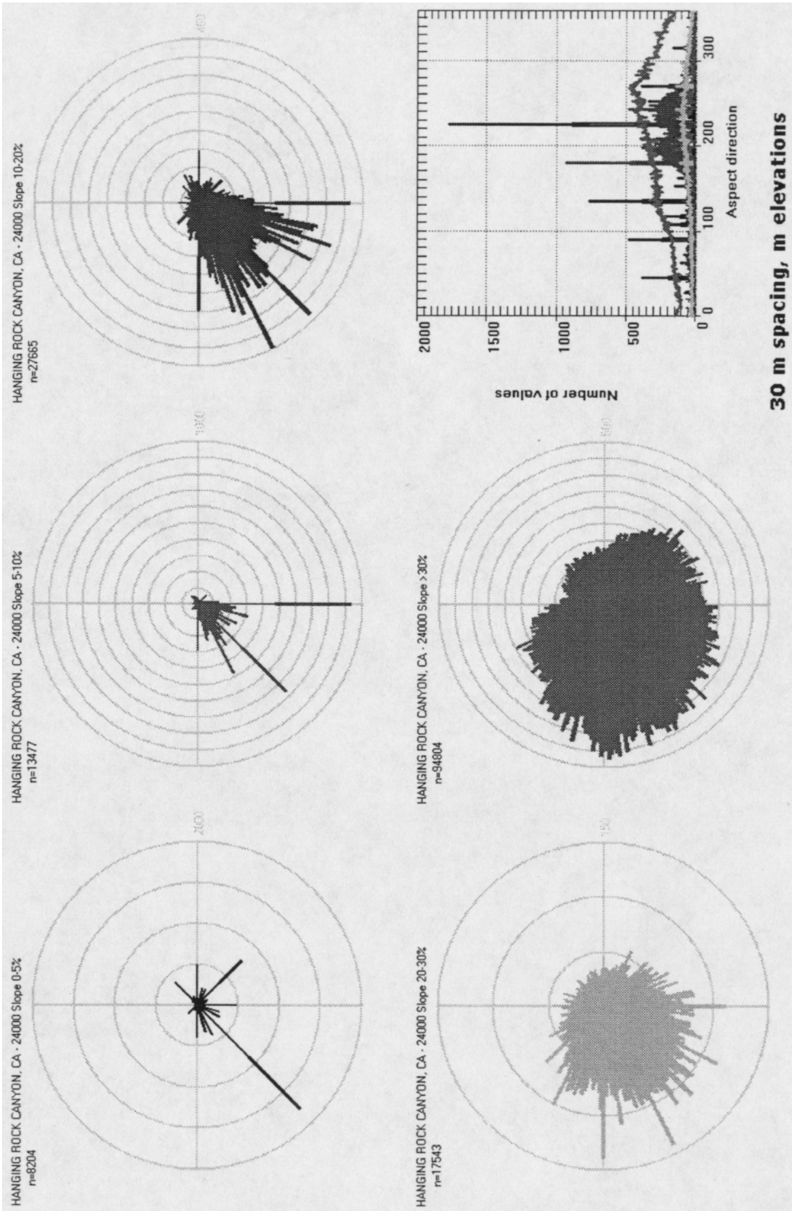

Fig. 6. Aspect distributions for the Level 2 Hanging Rock Canyon 30 m DEM, divided by slope class. This DEM has elevations in meters.

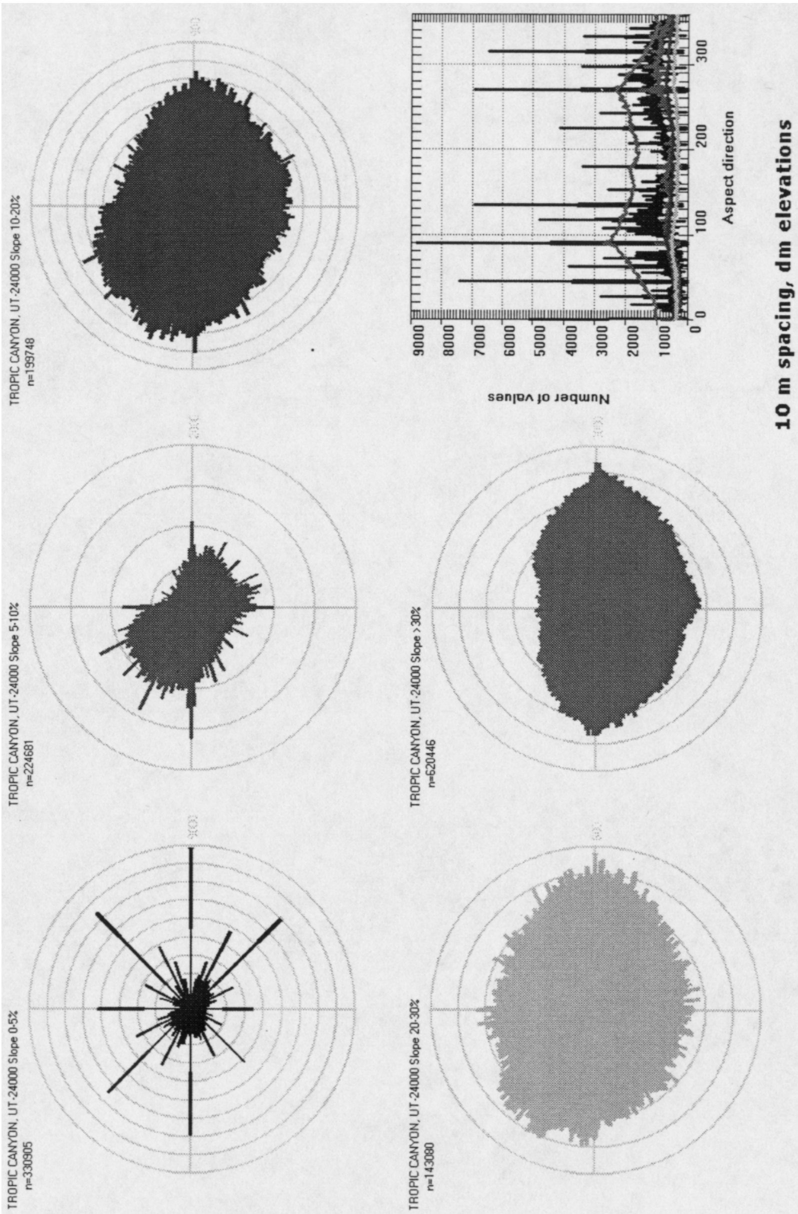

Fig. 7. Aspect distributions for the Level 2 Tropic Canyon 10 m DEM, divided by slope class. This DEM has elevations in decimeters.

in different physiographic provinces, compared to the steepest adjacent neighbor algorithm.

Since the eigenvector technique relies on the slope as input, Fig. 5 shows the organization parameter for level 2 DEMs calculated with the two slope algorithms. Scatter is minimal, the graph's slope is close to 1, and the differences do not correlate with the physiographic province. The eigenvector technique appears to extract organization independent of the slope algorithm use.

ASPECT ALGORITHM

Selection of an aspect algorithm presents much less choice than that of a slope algorithm, because extending many of the slope algorithms would result in a very limited number of possible aspect directions. Guth (1995) suggested use of the eight nearest neighbors with even weighting, and that algorithm has been used here. However, this algorithm does not provide an even or uniform distribution of aspects.

Figure 6 shows the aspects for a 30 m DEM. Note the spikes in the aspect distribution, especially prominent for the low slope parts of the DEM. Aspects at 45° intervals are overrepresented, and the algorithm appears to work well only when the slope exceeds 30%. The problem originates in the discrete nature of the elevations: with meter elevation resolution and 30 m spacing, the basic slope values only change by 1/30. To verify this assumption, Fig. 7 shows the aspect distributions for a 10 m DEM with elevations in decimeters. This allows slope values to change by 1/100, and in this case the algorithm appears to produce uniform and natural aspect distributions if the slope is steeper than 10%.

RESULTS

Table 3 summarizes the results of the comparisons of DEMs at different scales or sources. The correlation coefficients for both average slope and average elevation exceed 0.95 for all the comparisons, but with these sample sizes such correlation coefficients still allow some scatter and some significant anomalies. The organization parameter shows more scatter and lower correlations.

1. Continental data sets

The continental data sets agree with each other extremely well for average slope and average elevation, and less well for organization level. Table 3 shows correlation coefficients greater than 0.99 for elevation and 0.95 for slope, and as low as 0.51 for organization. GTOPO30 and GLOBE show the strongest correlation, and both have complete coverage of the world. DTED level 0 does not include Antarctica, and still has a large gap in the Amazon Basin.

Despite correlation coefficients for average elevation exceeding 0.99, differences in average elevation for 1° cells can exceed 2000 m. Six cells in the Andes of Peru and Bolivia have differences this large between DTED and GLOBE, and one has a difference exceeding 3000 m. This suggests that for parts of the world the continental data sets still have significant problems.

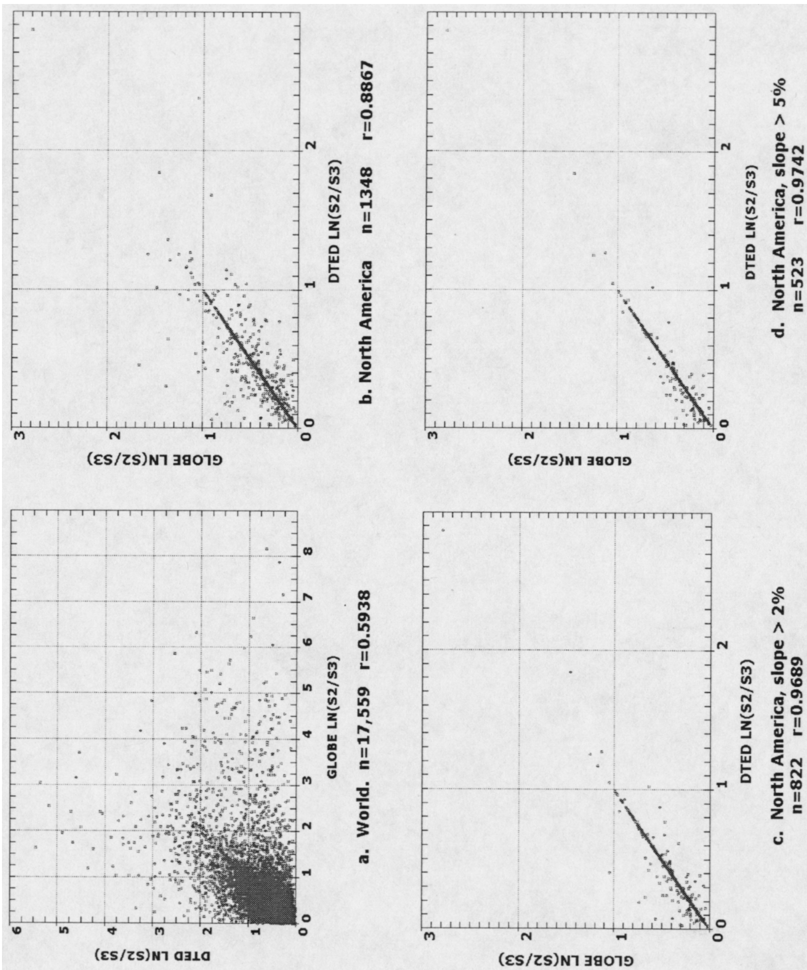

Fig. 8. Comparison of the organization parameter ln(S2/S3) calculated from DTED Level 0 and GLOBE for 1° cells. Note that (a) has a different scale than the others.

To investigate how well the continental data sets work in regions with good digital representations of topography, Fig. 8 shows the scatter plots for organization plotted from DTED and GLOBE. Figure 8a shows the global data, with a great deal of scatter and a correlation of 0.594. With the data restricted to part of North America (N23–N54, and W130–W73), Fig. 8b shows much less scatter and an improved correlation of 0.887. Restricting the data to regions with slopes greater than 2% and 5% in Figs. 8c and 8d increases the correlation even further to 0.97. Organization values have the least reliability in regions of low slope.

Assessing the accuracy of DTED Level 0 versus GLOBE or GTOPO30 remains beyond the scope of this work, because it likely varies regionally. The tremendous differences in average elevation noted above occur on the eastern flank of the Andes, where DTED shows the average elevation in one cell to be over 2000 m higher than the cell immediately to the east, and neighboring cells do not even remotely match along their common edge. Only a few of the cells in that region used higher resolution DTED as their source, and most of the others show only the grossest outlines of topography. GTOPO30 and GLOBE improve the elevation picture somewhat in that region, but clearly show which cells had high resolution source data available. The SRTM 30″ global set has just been released (summer 2003), and should now be used for this scale analysis.

2. Continental versus regional DEMs

This comparison must be restricted to the United States because of the lack of publicly available data elsewhere. Table 3 shows the comparison of about 940

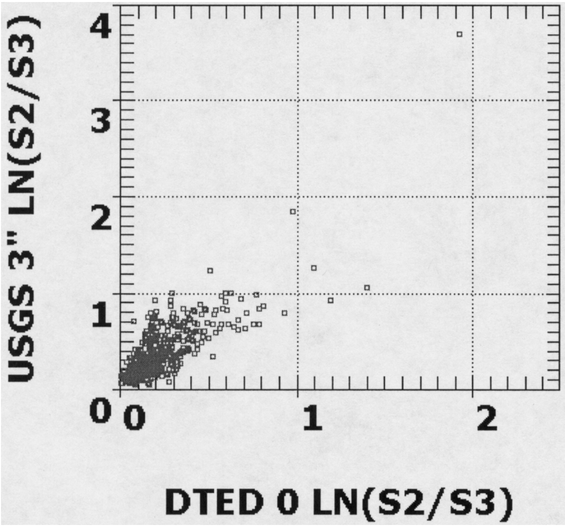

Fig. 9. Comparison of the organization parameter between DTED 0 and the USGS 3″, 250K DEM. This shows the 432 cells covering the United States with an average slope in the USGS DEM greater than 5%.

Table 4. USGS 250K versus 24K, 7 1/2′ tiles.

Average slope	Number of 7½' tiles	Organization Parameter Correlation Coefficient r
All data	34,887	0.473
>2%	23,241	0.612
>5%	13,026	0.757
>10%	7,956	0.818
>20%	3,598	0.818
>30%	1496	0.835

1° tiles for DTED 0, GLOBE, and GTOPO30 with the USGS 250K DEM. The three continental data sets have slightly different numbers of tiles because of differences in continental masking. Average elevation and average slope correlate almost perfectly, showing that the continental DEMs accurately capture this aspect of topography.

Organization correlates less well, with correlation coefficients around 0.68. As with the comparison among the continental DEMs, the disagreements tend in occur in the flatter DEMs. For the DTED 0 comparison with the USGS 3″ 250K DEM, the correlation coefficient increases from 0.6802 (n = 946) for all data, to 0.7314 for DEMs with an average slope greater than 2% (n = 642), and to 0.7875 for DEMs with an average slope greater than 5% (n = 432, Fig. 9). Areas of different slope will occur within 1° cells, so that low slope areas will produce different estimates of organization when aggregated over the entire cell.

3. *Regional versus local DEMs*

Table 3 shows that the USGS 250K and 24K DEMs show almost perfect correlations in average elevation and slopes. At the quadrangle level, despite severe contour line ghosts, the 250K DEM accurately depicts average terrain characteristics. The organization parameter between the two series correlates less well, but as Table 4 shows, the flat DEMs account for most of the poor correlations.

4. *Scale in local DEMs 10 m versus 30 m*

Somewhat surprisingly, Tables 3 show that for these geomorphic parameters the 10 m DEMs do not provide increased precision. The 10 m DEMs are visually vastly superior in the fine details they provide, but produce essentially identical statistical results. Even the organization parameter shows a high correlation coefficient, and it only increases from 0.954 to 0.981 as average slope increases from 2% to greater than 30%.

5. *Quality in local DEMs*

USGS produces two levels of DEMs, and in this sample they were present in almost equal numbers. Table 5 shows how the calculated organization parameters correlate as the average slope in the DEM increases.

Table 5. USGS 24K, 7 1/2′ tiles, Level 1 versus Level 2.

Average slope	Number of 7½' tiles	Organization Parameter Correlation Coefficient r
All data	6476	0.545
>2%	6454	0.544
>5%	5940	0.606
>10%	4695	0.706
>20%	2909	0.757
>30%	1586	0.890

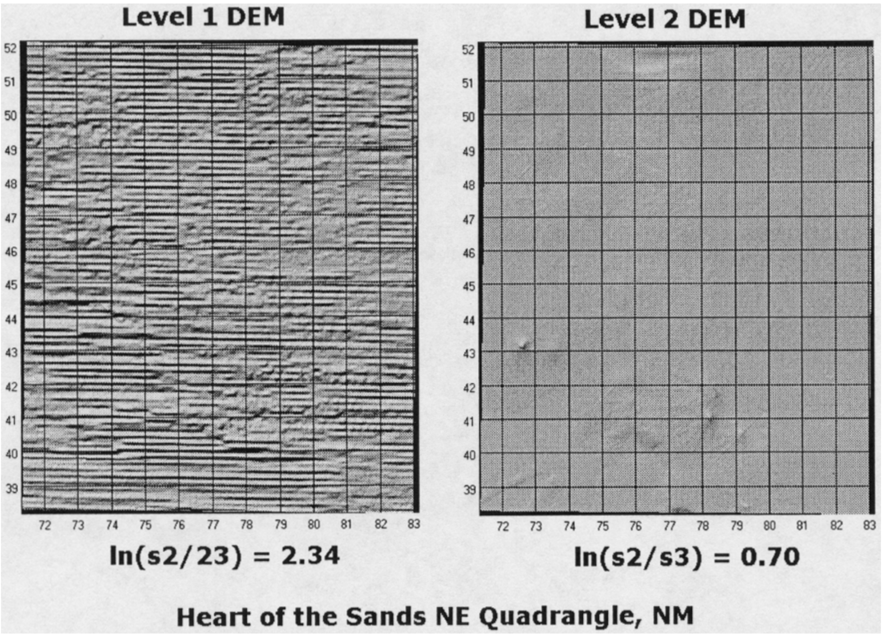

Fig. 10. Shaded reflectance maps of Level 1 and Level 2 DEMs of the same quadrangle in New Mexico.

One reason for the scatter in this comparison is the wide range in quality of the level 1 DEMs. Figure 10 shows the level 1 and level 2 DEMs for a very flat region, and the Level 1 DEM is one of the worst examples available. Its calculated organization parameter would rank it as one of the most organized in the country, but as the Level 2 DEM shows, the organization is entirely an artefact of the DEM creation process.

6. *Average slope at different DEM scales*

As has been determined in previous studies, computed slope increases as the

Table 6. Comparison of average slope from different scale DEMs.

Small Scale DEM and Tile Size	Sample Size	Slope Ratio to Large Scale DEM
GLOBE Slope (1° tiles)	n=941	78% 250K slope
250K Slope (7½' tiles)	n=51,345	86% 24K Slope
24K level 1 Slope (7½' tiles)	n=6476	85% 24K Level 2 slope
24K (30 m) level 2 Slope (7½' tiles)	n=472	100% 24K (10 m) level 2 Slope

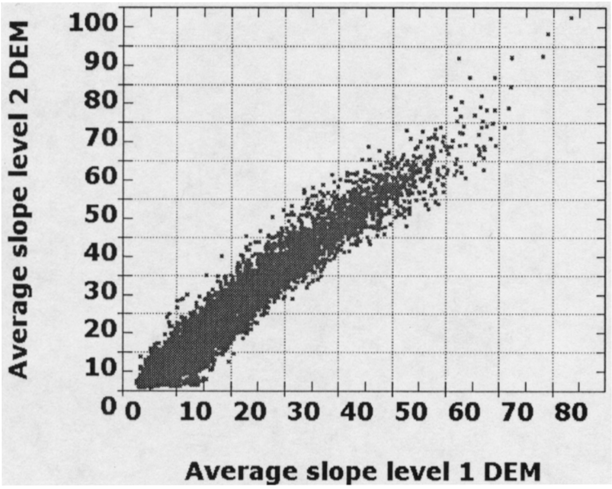

Fig. 11. Comparison of the average slope (steepest adjacent neighbor method) for 6226 30 m DEMs with both Level 1 and level 2 coverage.

size of the sampling region decreases. This study quantifies that relationship, using large samples of real DEMs. Table 6 shows the relationship observed, and Fig. 11 shows the relationship between independent level 1 and level 2 DEMs of the same quadrangle. Much of the scatter is likely due to a minority of very poor quality Level 1 DEMs (such as that in Fig. 10). The only surprise was that 10 m and 30 m DEMs produced identical average slopes.

7. DEM quality control

First attempts to create bivariate plots of geomorphic parameters from the USGS 24K DEMs led to the recognition that (1) overedge and extremely flat DEMs produced Door statistics, and (2) most outliers on the plots represent problems in the source DEMs. This problem was severe enough that a "BAD_DEM" field was added to the database, and a quick way to flag these DEMs was incorporated into MICRODEM. Figure 10 shows one particularly bad DEM, identified with striping (Oimoen, 2000) when it was visually inspected as a candidate for the most organized DEM in the United States.

Table 7. “Bad” 24K DEMs by series.

DEM Series	Number Available	Number “Bad”	Percent “Bad”
Level 1, 30 m	19,444	256	1.31%
Level 2, 30 m	30,835	68	0.22%
Level 2, 10 m	1066	6	0.56%

Average quadrangle slope initially revealed the most defective DEMs, because the bad elevations are usually so much larger than the others that they affect the average. Figure 1 shows the strong relationship between average quadrangle slope and the flatness parameter. After first flagging flat and overedge DEMs, a number of outliers remained. These had a higher average slope than their flatness parameter would indicate. Clicking the point on the graph brings up the database table for that record, and a click there opens the DEM. When visual analysis confirms that the DEM is defective, it can be flagged and ignored for further analysis. This pair of variables works because bad values affect the arithmetic mean used for average slope more than they affect the vector average used for the flatness parameter.

The following errors have been identified: (1) large rectangular regions of the DEM with uniform, erroneous elevations (probably a flag representing regions of no data, appropriate to processing software but not to the SDTS DEM profile); (2) a single partial row or column of bad elevations along one margin of the DEM (often one or two bad postings); (3) a single spike elevation, in some cases where a posting in feet was inserted into a DEM in meters; (4) snaking “lines” of bad elevations within the DEM; (5) DEMs mislabeled as feet or meters instead of the correct value, which show up in regional maps of average elevation where they are either three times or one third the elevation of their neighbors; (6) lakes with a uniform elevation that does not match the surroundings, or the height on the topographic map. The striping artefacts in some level 1 DEMs (Oimoen, 2000) are not included, because I have not been able to automate their identification, and assessing their severity remains a very subjective process.

At present at least 330 of the 51,345 DEMs downloaded from the USGS have been flagged as defective; this is a minimum estimate because only the most obvious statistical outliers have been examined visually to confirm the DEM quality. After redownloading a sample of these, it is clear the files posted on the web were defective and not the download process. With compressed downloads, a faulty download is more likely to produce a file that will not decompress rather than one with erroneous elevations. Table 7 suggests that over 1% of the Level 1 DEMs have errors, and that for Level 2 DEMs the error rate has decreased. This analysis may not reflect the current status of the USGS data because (1) the USGS performed a major reprocessing effort in the summer of 2001 to correct registration problems with some DEMs, (2) increasing numbers of 10 m DEMs are now available, and (3) it is not currently feasible to duplicate collection of the 50,000 DEM data set.

Maximum point slope is probably the single best parameter for flagging bad DEMs. While a few DEMs have valid huge point slopes, like the volcanic neck at Ship Rock, New Mexico (slope 1561%) or the cliff face of Half Dome in Yosemite National Park (slope 1553%), excessive point slope values over 1000% almost always represent bad postings in the DEM (at least 291 of 364 bad DEMs in this sample). While many of the errors in these DEMs are not severe and would not significantly affect most uses of the DEM, they could be eliminated with a simple quality control step. The DEM should be displayed as a shaded reflectance map, the location of the steepest point slope flagged, and the elevations of the postings surrounding the point displayed. The maximum slope could be compared to the distribution of maximum slope with the Fenneman province, and if the maximum slope in the DEM occurs in a pit, the point almost certainly represents an error. The DEM could then be accepted, or additional edits performed. While this sample was downloaded in the summer of 2000, some of the bad DEMs are still present on the commercial servers now distributing the USGS data. Osborn and others (2001) describe the challenges faced by USGS in developing quality control methods for the DEMs.

CONCLUSIONS

- Different slope algorithms behave differently depending on the physiographic province. Most of the difference between the steepest adjacent neighbor algorithm and the four nearest neighbors algorithms is not due to the small number of peaks, ridges, and valleys, which can have huge differences, but to the vast majority of points which cannot easily be categorized over a nine point region.
- Aspect algorithms do not work well in low relief regions, producing too many aspects at 45° intervals. They never work well at very low slopes, and the steepness at which they begin to produce uniform results appears to be related to the ratio of vertical resolution to horizontal resolution in the DEM.
- Different scales of DEMs accurately capture average elevation, which correlates very strongly across scales.
- Different scales of DEMs accurately capture average slope, which correlates very strongly across scales. The absolute value of average slope increases as the resolution of the DEM increases (post spacing decreases), although there appears to be no change between data spacings of 10 and 30 m.
- Different scales of DEMs accurately capture terrain organization, both in orientation and magnitude. The correlation is weakest in low slope regions, probably because of problems with the aspect algorithms, and is strongest in moderate to high relief areas.
- Geomorphic parameters can provide quality control for DEMs. Experience with the USGS DEMs suggests that a simple maximum point slope check should be performed on all DEMs, with excessive values over 1000% almost always representing bad postings in the DEM. This procedure should be implemented in the DEM production process.

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